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DEVELOPMENT OF EXPLOSIVE
TECHNIQUES IN METAL FORMING.

Status Report No. 2

January 1, 1963 through June 30, 1963

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FOREWORD

The present research project comprises studies of explosive techniques for sheet metal forming, welding and compaction of powder. The more basic problems in these processes have been emphasized, but also technological and economical aspect are being studied.

During the first year of the project, extensive preparations with respect to facilities, tooling etc. have taken place, but also systematic experimentation has reached a satisfactory stage of development.

In the work under this contract we cooperate with the Norwegian Defence Research Establishment. As of July 1, 1962 the U.S. Government through The Mutual Weapons Development Program is jointly sponsoring the project.

This report covers the period from January 1 through June 30, 1963.

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ABSTRACT.

In the first year of this project, development of experimental facilities, tooling and instrumentation has been the predominant activity. This phase of the work has now largely been completed and systematic experimentation is currently taking place in all the main areas of the program.

Industrial feasibility studies have been based on full scale experiments with a few industrially important components and on an extended industry survey. The first experiences with a vacuum compacted sand die are promising.

Preliminary studies of dynamic plasticity indicate that detailed information about instantaneous plastic deformation, shape of the cup, normal velocity of blank and horizontal velocity of bending wave can be obtained by means of the experimental technique chosen.

The effect of shock intensity and high strain rates on structural changes in austenitic stainless steel (SAE 304) have been shown to be appreciable. Improved x-ray techniques for identification of mechanical twins and other structural defects are being developed.

Explosive welding of all combinations between stainless steel and aluminum have been studied. The occurence of brittle instrumentallic layers, local melting, recrystallization and ripple formation have been demonstrated.

CONTENTS

1.0 INTRODUCTION

During the period covered by this report the development of the project has proceeded in satisfactory agreement with the plans outlined in status report no. 1. Some delay in the delivery of equipment and tools as well as unexpected repairs of the detonation pit have only caused minor time losses.

A substantial part of the work has been concerned with construction and testing of tooling and instrumentation for studies of dynamic plasticity, high temperature forming and technological and economical feasibility of certain explosive forming operations. This work has largely been completed so that actual experimentation from now on can become the predominant activity.

The testing materials and the larger instrument units are also becoming available as planned. The fatigue machine was the last of the instruments to arrive, but is currently being installed in our laboratory. The electron probe microanalyzer has already been used in a few preliminary experiments, but the results are not commended in this report.

The studies of structural changes in austenitic stainless steels as a function of shock intensity and forming speed, have indicated that this material is very sensitive to these parameters. Development of x-ray techniques for identification of twins and other structural defects is well under way and will probably be completed during the next phase of the work. The same applies to magnetic methods for quantitative determination of ferritic and mertensitic phases in the deformed steel. Thus far, all experiments have been conducted at room temperature. In the following, however, also sub zero- and elevated temperature experiments will be incorporated. Corrosion testing and more extensive mechanical testing will also take place.

Preliminary results of dynamic plasticity studies indicate that the experimental technique chosen probably is capable of providing information required for a fundamental study of the deformation process. Extensive data concerning instantaneous plastic deformation and

geometry as well as velocity of blank and bending wave will be accumulated during the next phase of the work. Further theoretical studies will attempt to develop mathematical formulations for these processes.

The high temperature forming die has been completed and is scheduled for testing. It is expected that part of the actual program will be realized within the next report.

The welding experiments have been concerned with the influence of relative position of the plates, surface cleaning and shock wave modification. All combinations of stainless steel and aluminum have been used. Brittle intermetallic phases were found to be detrimental in the steel/aluminum combination, and indications of local melting and recrystallization were observed in aluminum/aluminum welds. In the further work, importance of vacuum will be studied and new metal combinations will be incorporated. The analytical and mechanical testing of the weld zone will be continued and expanded.

Some preliminary experiments on compaction of powders have been carried out, using niobium powder. This work will now be intensified.

2.0 MATERIAL AND INSTRUMENT PROCUREMENTS

The sheet materials listed in Table I of status report no. 1 have all been ordered by now. All steels except VascoJet 1000 and AM 355 will be delivered by the Gebr. Bøhler & Co in Austria. The same producer will also deliver the following additional steels:

1. Bøhler, NMH, containing 0.4 C, 0.7 Cr, 1.3 Ni, and 0.4 Mo.
2. Bøhler high speed steel, Mo Rapid Extra 9, containing 0.8 C, 2 W, 9 Mo, 4.3 Cr, and 1.2 V.

These steels are incorporated in the investigation because of their convenient transformation properties.

VascoJet 1000 and AM 355 will be delivered by Republic Steel in U.S.A, and tungsten sheet specimens will be delivered by the Bureau of Naval Weapons.

The powders required for the investigation will be delivered by the Glidden Corp. in U.S.A. and H.C. Stark Berlin, Germany.

A number of these materials have already arrived and the rest are due in good time before they are needed for experimentation.

The Cambridge electron probe microanalyzer is now installed and has been in use for preliminary experiments.

The Amsler 2 t high frequency fatigue machine is currently under installation. Preliminary experiments with explosively formed SAE 304 steel have been conducted by the producer of the machine (Amsler Corp. in Switzerland).

3.0 GENERAL FEASIBILITY STUDIES

3.1 Introduction

The objective of this program is to accumulate practical knowhow relating to technological and economical aspects of explosive forming. This will be accomplished through experimental fabrication of industrially important products.

During the reported period, an extended industry survey has been conducted and fabrication of two selected parts has been started. Tooling for other parts is under construction and will be completed in the next phase of the program. The experience gained clearly indicates that continued feasibility studies are essential both for the industrial promotion of explosive forming in Norway and for the more basic studies under this contract.

3.2 Industry survey

Eight industrial companies in Norway and the Royal Armament Research and Development Establishment (RARDE), as well as the Royal Ordnance Factory (ROF) in England have been visited last spring. In general, the interest in explosive forming was appreciable in both countries, but no civilian production seemed to have emerged.

The feasibility of explosive forming was discussed in connection with such civilian items as are exemplified in the list below:

1. Domes and pressure vessel ends of stainless and mild steel.
2. Small aluminium boats.
3. Large mild steel and aluminium plate constructions for ship building.
4. Plate heat exchangers of stainless steel.
5. Plate evaporators of stainless steel.
6. Composite plate and sheet materials.

7. Internal cladding or lining of containers and tubes for chemical industry.
8. Various parts for gas turbine engine.
9. Hardening of manganese steel components.

Economic advantage is indicated for many of these items considering the industrial conditions prevailing in Norway. Especially item 1) represents an interesting group of products within food and chemical industry. In Holland and England (10)explosive forming of stainless steel domes and pressure wessel ends is claimed to become economical at diameters above 0,8-1 m. It may well be that this limit is even lower in Norway. It is expected that similar size limitations also apply to items 4) and 5). Production runs in the range from some ten parts up to a few thousands each year are required for these products.

The outlook for a small-boat production is less clarified. No doubt, explosive forming can be used to advantage when double curvatures are required. However, the need for such contours in modern motor-boats apparently is uncertain. In life-boats the smoothness of the curves is so unimportant that very simple and inexpensive rolling techniques can be used. Another main obstacle to development in this field is the competition from plastics. Reliable information about the economy of explosive forming in boat-building is required as a basis for estimation of future trends.

In the ship-building industry the number of parts required per ship is frequently very small - often only one. Furthermore, the size of the part is usually very large. Tooling for explosive forming can then hardly be justified, since the necessary manual work is obviously less expensive. An increase in the number of parts to be formed may be anticipated as standardisation proceeds in the ship building industry, but at the present only a limited scope can be found for explosive forming.

Items 6) and 7) seems to be of considerable commercial interest. This is partly due to the fact that a larger variety of sheet explosives is becoming available at substantially reduced prices in Europe. Thus, in the case of cladding, a better economy and an easier attainment of optimum processing conditions can reasonably be anticipated. Some of our contacts held the opinion that explosive cladding already had economic advantage over conventional methods for several material combinations. They claimed that product quality and process control were, in fact, limiting factors today. At least two companies (one in England) were actively engaged in development work in this area.

Item 8) represents a well known field of application. Until recently no commercial production of gas turbine engines has taken place in Norway. However, there is reason to expect a change in this situation soon.

Item 9) was claimed to be of interest in connection with wear resistant parts in digging- and crushing machines produced by a local company.

A number of other items, not listed, gave additional support to a relatively optimistic overall outlook for explosive forming in Norwegian industry. Some of the applications for military purposes are discussed below.

3.3 Fabrication of Rocket Nose Cone Sections

3.31 Introduction. The nose cone was required by the Norwegian Defence Research Establishment for a guided rocket currently under construction. After several unsuccessful attempts using conventional spinning techniques, explosive forming was chosen for further experiments.

The cone had to be fabricated in two sections in order to facilitate installation of instruments in the rocket interior.

3.32 Experimental. The dies shown in Fig. 1 where machined from low carbon steel castings (German specification GS-45). All cones were prefabricated from 1 mm 57S, H14 aluminium sheet, using one longitudinal weld. The position of the cone prior to forming is indicated in Fig. 1. Only the parabolic central portion of the formed cone is subsequently used in the rocket. The conical end sections were mainly designed for sealing purposes. Provisions for evacuation of the die cavity are also indicated in the figure.

A detonation fuse[x)] consisting of 10 grams Tentrite per meter was used in all experiments. The charge was mounted axially in the die by means of a thin rope going through wooden discs at both ends of the cone. Douglass' (1) scaling laws developed for tubings and centraly positioned line charges were used as a guide. A fuse length corresponding to about 3/4 of the cone axis was found to give complete forming under water and at a vacuum of 4 mm Hg in the die. However, a second shot was necessary in order to reduce spring back. The dimensional tolerances in the finished product were of the order of 0,1 mm.

Fig. 2 shows two successfully formed sections which were subsequently used in an experimental rocket. Originally, difficulties were experienced due to cracking of the weld, but after correction of the welding conditions no failure occured.

3.4 Fabrication of Air Intake Ducts

3.41 Introduction. At the main repair workshop of the Norwegian Air Force, fabrication of sheet metal replacement parts is frequently very time consuming and difficult with the available equipment. A valuation of some typical geometries, taking into account the number of parts usually required, seemed to indicate that explosive forming in many cases might be feasible as an auxiliary fabrication method. For further elucidation of this question, a rather complex part from the air intake duct of a F-86 Sabrejet airplane was selected for a series of full scale experiments.

x) Delivered by Norsk Sprengstoffindustri A/S.

3.42 Tooling. A photograph of the forming die is shown in Fig. 3 and the constructional details are indicated in Fig. 4. The die was made of concrete with 6 mm glass-fibre reinforced epoxy lining in the die cavity. A plaster of Paris model was used for shaping of the lining. The "draw ring" was constructed from a mild steel tube of 3,5 cm diameter, internally filled with concrete. Epoxy resin was used for assembly of the lining and the draw ring.

Five steel bolts were anchored in the concrete for attainment of clamping force on the 12 mm mild steel pressure ring. A certain controlled variation of pressure along the ring was accomplished through the system of girders shown in Fig. 3. Trimming of the workpiece is done after forming to obtain the correct shape of the intact duct

3.43 Experimental. In the preliminary experiments 1,5 and 2,5 mm thick 2S, H12 aluminium sheets have been used. It was also found convenient to start with air shots, using a 2 cm thick rubber "plug" between the blank and a 10 g/m tentrite detonating fuse. On top of this, a 5 cm thick layer of sand served the purpose of holding the fuse in position and improving the energy transfer to the blank.

After the first shot, water was filled in the cavity to serve as transfer medium in subsequent shots. A vacuum of about 10 mm Hg in the die cavity was easily established through sealing around the blank edges with plasticine.

The first experiments clearly demonstrated the difficulty of the forming operation; severe wrinkling, overforming and fracturing taking place. However, conditions gradually improved and the fairly successful result shown in the background of Fig. 3 encouraged a more systematic variation of the following parameters,

1. Weight and geometrical arrangement of detonating fuse at various forming stages.
2. Shape of the blank.
3. Thickness of the blank.
4. Magnitude and distribution of pressure on the flange.

In order to facilitate the study of material flow, a 5 cm network was painted on the surface of each blank.

The preliminary results seem to indicate that blank geometry rather than clamping pressure controls the drawing in of material from the flange. Applying the standard formula D-d/D=constant (D = blank diam., d = draw ring diam.) to those sections of the draw ring which have nearly circular curvature, fairly uniform drawing conditions were finally attained.

Variation of clamping force within the permisible limits had little effect on the tendency to wrinkling. An increase of the blank thickness from 1,5 to 2,5 mm, however, reduced buckling and wrinkling noticeably.

A charge weight of about 24 g arranged as one loop in each of the two bays of the free blank surface, was found to give uniform drawing with a minimum of wrinkling. A degree of forming corresponding to about 25 % of the finished product was typical. Heavier charges tended to produce overforming and rupturing. The experiments further indicated that blank motion as influenced by location and local concentration of the charge, was of considerable importance. If forming continued in one part of the work piece after it had terminated in another, severe distortion always took place.

A second shot, using the same charge weight and arrangement as before, gave a local stretching of up to 25 %. A third shot usually ruptured the work piece, thus necessitating a process anneal. Due to unsatisfactory control of the annealing temperature in preliminary experiments, the final forming operation have to be repeated. It was indicated, however, that a satisfactory result might be anticipated in the end.

One important conclusion of these experiments is that the economy of an explosive forming process may be significantly influenced by the expenditures necessary for extensive development work. This points out the need for a more quantitative understanding of the forming mechanisms.

3.5 Further Work

The feasibility studies will in the next phase of the project comprise the following items:

1. Completion of experiments on the air intake duct. Analysis of economic aspects.
2. Fabrication of a 85 x 23 cm^2 stainless steel heat exchanger using an epoxy lined concrete die.
3. Further analysis of product selection and explosive production in Norwegian industry, possibly supported by experimental activities.

4.0 DEVELOPMENT OF A VACUUM COMPACTED SAND DIE

4.1 Introduction

The main purpose of this part of the program has been to develop a versatile and inexpensive forming die, in which a thin shell, defining, the die cavity, can easily be exchanged.

Preliminary experiments had indicated that "vacuum compacted", unbonded sand could be used as a satisfactory backing for the die shell. It was anticipated that a die of this type would be very useful in the present program and might ultimately contribute to the expansion of the field of application for explosive forming.

4.2 Design and Operation of the Die

A photograph of the die is shown in Fig. 5, and the construction principles are given in Fig. 6. Only a shallow die cavity is demonstrated in the drawing. However, much deeper shells of arbitrary geometries can be accomodated in the system, since the size and positions of the reinforcement plates can be varied at will.

Fig. 6 also indicates the necessity of a steel draw ring on top of the epoxy flange. It would seem possible, however, that forming of thin-gage materials could be done without this extra drawring. In the case of sizing, of course, only the pressure ring is required. This also applies to many dimpling and corrugating operations, involving little drawing in from the flange.

Evacuation of the sand system is easily accomplished through a vacuum line in the basis flange. The die cavity presents more of a problem when no extra draw ring is being employed. In this case, a vacuum line has to pass through the shell itself at one of several locations. The various alternatives will be studied experimentally in order to find the best solution. In general, extensive use of O-rings has been selected for sealing purposes, in order to simplify and speed up the operations.

After the die shell has been fastened, the die is turned upside-down, and vibrated in order to eliminate air pockets in the sand system. When vacuum has been established, the die is turned back to its normal position and operated in the usual manner. Vacuum will be maintained in the sand system for extended periods of operation. If, however, the geometry of the die cavity tend to change under the influence of repeated shots, periodic inflations of the sand system may become necessary.

The die shown in Fig. 5 has been used in a few preliminary experiments with 2 mm Al sheet blanks and a thin- walled plastic shell. The parts were successfully formed and no damage was done to the shell.

4.3 Further Work

The die will mainly be used in connection with the feasibility studies outlined above. In this work special attention will be paid to the following items:

1. Methods of evacuating the die cavity.
2. Draw ring requirements.
3. Stability of die.
4. Dimensional tolerances in product.

5.0 DYNAMIC PLASTICITY

5.1 Introduction

The primary objective of this program is to perform a detailed experimental and theoretical study of the plastic deformation and the geometrical changes occuring in shock loaded, circular plates restricted at the circumference. Existing theories for this forming process will be valued in light of the experimental evidence becoming available. Furthermore, an analysis of the importance of transient disturbances originating at the clamped edge will be attempted, using modern theories of shock wave propagation and interaction in metals.

The experimental technique chosen is based on the assumption that both instantaneous deformation and shape of the blank can be satisfactorily "quenched" in a steel die which, at the moment of impact, has the same shape as the blank.

In the folowing is given a brief account of the experimental developments. Theoretical considerations have been omitted since they have not reached a stage of development which warrants presentation in this connection.

5.2 Tooling and Instrumentation

The forming die shown in Fig. 7 is a slightly modified version of one of the dies presented in the first status report. The redesign was done mainly for the purpose of speeding up the die operation. This has been accomplished through the use of a lock ring together with larger bores for the clamping bolts through cover flange, draw ring and adapter ring. The die can now be disassembled after a slight clackening of the screws.

A steel anvil which can be fitted into the die cavity and two adapter rings have been fabricated, permiting draw depths of 1.3 - 2.5 - 3.4 and 6 cm in the same die.

Determination of blank velocity has thus far been based upon measurement of the time-interval between "start of motion" and arrival at the die surface. Signals from electrical contacts are fed to a cathode ray oscilloscope of known sweeping speed, or directly to electronic counters. The connecting circuits have been arranged so as to give negligible time delay.

The construction of the planar contact extensively used in preliminary experiments, is given in Fig. 8. A suitable signal voltage is supplied between the die and the aluminium ribbon constituting the two electrodes of the contact. A hole of 1 to 2 mm diameter is punched in the insulating tape separating these electrodes. Upon compression of the contact, the aluminium ribbon makes contact with the die through the perforation. The total thickness of the contact is only 0.1 to 0.2 mm.

It has been shown that this contact is reliable when operated at the die surface. When the blank is moving at a high velocity ($\sim$100 m/sek), the signal from the contact is estimated to deviate from the true moment of impact only be some two microseconds. At lower blank velocities, as will occur in the corner of the die, this deviation will increase in proportion to the velocity reduction. For some measurements it may thus become necessary to employ small pin contacts instead of planar contacts.

The signal required for the start of motion must be clearly defined in relation to the accelleration period of the blank. There is some experimental evidence in earlier investigations (2), indicating accelleration periods of the order of 100 micro seconds. This could have a significant influence upon the accuracy of the estimated blank velocity values.

In order to clarify this point, signals from the following locations have been compared:

1. Ionization gauge in contact with the explosive.
2. Planar contact in contact with the upper surface of the blank.
3. Pin contacts at various distances below the blank.

The planar contacts employed in these experiments did not have the usual air vent, and additional coating had to be used for protection against water. However, the contacts were found to operate satisfactorily.

Blanks of 2 mm thickness, charges of 30 g RTX and stand off distance of about 13 cm were used in these experiments.

Fig. 9 shows an oscillogram with signals from positions 2 and 3. The distance from the blank to the pin contact was 0.3 - 0.4 mm. Considering the time scale of 10 micro seconds per mm, the two sharp peaks about 2 mm apart indicate a time differance of some 20 micro seconds. The response of the planar contact was estimated on the basis of the time differance between signals from positions 1 and 2. A rapid and satisfactory response was indicated.

Signals from pin contacts at various distances below the blank, failed to demonstrate any accelleration distance.

The exploratory experiments outlined above have indicated that accelleration of the plate takes place over a very short distance and within a time period of about 15 micro seconds. Thus, it appears that planar contacts and pin contacts both can be used for the purpose of defining the start of blank motion. However, small corrections may have to be applied in the calculation of velocities.

Further experiments will be carried out with planar contacts and with dual pin contacts which can give separate measurements of blank velocity at the surface. Furthermore, tests with planar contacts on the internal blank surface will be continued. Thus far, a thin lead strip have been used as a backing, in the latter case, in order to provide inertial forces on the contact.

5.3 Initial Forming Experiments

Stainless steel, type SAE 304, was selected for initial studies since this material was also required for studies of structural changes due to explosive forming (see chapter 6.0). Plates of 33 cm diameter and 2 mm thickness were used after annealing for

about three hours at 1050 ^{o}C in an argon atmosphere. The plates were rapidly cooled between brass blocks in order to prevent distortion and carbide precipitation.

Spherical charges of 45 grams RDX were initiated by means of a Briska No. 10 detonator at a stand off distance of 12 cm. The forming was carried out under water in the detonation pit.

Dow corning No. 32 grease was used for lubrication in the flange area where a constant clamping force was attained by means of a torquemeter. A vacuum of about 4 mm Hg was established in the die cavity.

The blank profiles and thinning effects after forming in 1.3 - 2.5 and 6 cm deep dies are given in Fig. 10. A fourth experiment was also conducted in which an "anvil" of balsa wood, under a thin layer of rigid polyurethane foam, completely filling the die cavity. A symmetrical and uniform 2 cm deep cup resulted, leaving the balsa wood in a highly compressed state. Thinning effects for this case will be recorded later.

The blank velocity was not measured in any of these experiments, but results obtained under similar forming conditions with mild steel blanks, gave values in the range from 150 to 200 m/sec. This would indicate that the stainless steel cups have experienced a very sharp impact with the die, as required for the structural investigations. The retardation in balsa wood, however, must nearly have eliminated this effect.

The thinning curves in Fig. 10 demonstrate non-uniform deformation in all cups. A typical feature of the curves is a nearly flat central region which gradually becomes smaller as the draw depth increases. It is assumed that this region corresponds to an area of the cup which is essentially flat during forming. The large thinning concentrated near the corners of the diesmay thus be ascribed to a "filling out" effect taking place after the central regions have been stopped by the die.

The thinning curves can probably be used as a basis for rough estimations of the cup profile at the various forming stages. This method will be used for a first approximation of the die profile to that of the cup at the moment of impact.

If the end point of the flat section of the thinning curves coincide with the bending wave originating at the circumference, estimation of the wave velocity ought to be possible on the basis of information in Fig. 10.

5.4 Further Work

In the continuation, the work will concentrate on the following items:

1. Improvement of contacts for velocity measurements.
2. Adjustment of die profiles in order to eliminate secondary deformation in the corners.
3. Variation of clamping conditions, charge weight and material thickness in conjunction with instrumentation and die corrections. Mild steel and aluminum will be the principal testing materials.

6.0 STRUCTURAL CHANGES IN AUSTENITIC STAINLESS STEELS DUE TO IMPACT AND HIGH STRAIN RATES

6.1 Introduction

Structural effects of explosive shocks have been reported in several metals and alloys. These effects include formation of martensitic phases in austenitic steels, (3,4) extensive twinning in both bcc and fcc metals (4,5,6) and, possibly, formation of a high density of point defects (4).The strengthening which is obtained in steels through explosive shocks has been related to martensitic phases and especially Verbraak has attributed deterioration of corrosive and mechanical properties in material subjected to explosive forming to structural changes brought about by the shock.

The purpose of this part of the program is to study the structural changes in austenitic steels under conditions met with in explosive forming with the aim of separating the effects of

1. incident shock wave
2. plastic deformation at high strain rates
3. impact with the die

The experiments described in section 5.3 were planned to give an optimum separation of these parameters. Samples for x-ray and metallographic examinations were sectioned from different positions in the flat bottom of the cup in order to compare the observations with the measured reductions in thickness.

6.2 Metallographic Examination

The most characteristic feature of the metallographic structure is the dense markings seen in the figures 12, 14, 15, 16 and 18. Some of these have the appearance of slip bands, others are similar to the markings observed in shocked 18-8 steel by Verbraak (6,7) and identified as twins. Examples of markings interpreted as twins are

shown at higher magnification in Figures 19, 20 and 21. Fig. 22 shows a grain where slip appears to be the predominant mode of deformation, although some twins are also seen. The slip plane and twinning plane in austenite are bbth (111), and it is not always possible to distinguish between slip bands and deformation twins from the micrographs alone. Our x-ray evidence is as yet inconclusive, and we rely partly on the extensive x-ray and electron microscope studies by Verbraak (7) on structures which have produced similar micrographs.

Most of the assumed twin markings contain finer contrast details indicating steps across the twins. These may be interpreted as resulting from the passage of slip or twinning dislocations across the twin. This will, according to Sleeswyk& Verbraak (8) leave a slip trace in the twin and a step in the twin-matrix interface. The directions of the observed markings acrcss the twins in the Figures 20 and 21, where the three sets of (111) traces permit the orientation to be determined, are consistent with such a description.

Markings indicating deformation twins were also found in some specimens which had been deformed during quenching in water and had not been subjected to subsequent explosive shock. Twins were not observed, however, in plates which were free from distortion during quenching. Quenching between brass blacks was satisfactory in this respect. The twins seen in Fig. 19 may, however, be a result of the quenching, as this specimen had been water quenched.

It should be mentioned that the system of diffuse "ghost lines" running through the grains, parallel to the rolling direction of the sheet, is a feature of the original material. The lines did not disappear even after annealing at 1050 $^{\circ}$C for 48 hrs.

6.3 X-ray Examination

Specimens were studied in a Siemens Texture Goniometer using Co radiation and pulse height discrimination, and in a powder diffractometer. Examples of texture diffractograms from a surface normal to the shock direction are shown in Figures 23 to 25. The irradiated area was approximately 5 mm^2. The diagrams reveal considerable broadening of the reflexions from each grain, as a result of explosive shock under all experimental conditions.

A technique is being developed to study the orientation of individual grains from texture diagrams with the special aim of detecting twins. Due to the presence of annealing twins, no definite conclusions have been arrived at so far.

From powder diffractograms, taken in a General Electric Diffractometer, lattice spacings and line widths were determined. Some preliminary results are given in Table I.

TABLE I

X-RAY LINE WIDTHS AND LATTICE CONSTANTS. SPECIMEN NORMAL TO SHOCK DIRECTION. FeK_a-RADIATION.

Specimen	half widths (in units of $s = 4\pi \sin \vartheta/\lambda$)				lattice constant
	(111)	(200)	(220)	(311)	(Å)
as annealed	-	.010	-	.013	3.594
soft impact	.013	.016	.014	.019	3.596
hard impact	.022	.03	.025	.04	3.595

The half widths were measured towards the low-angle side. The measurements are to be extended shortly when pulse height discrimination will be available also with the powder diffractometer. The present results indicate, however, a relatively larger half width for the (200) reflexion than for the neighboring (111) and (220) reflexion, pointing

to the presence of stacking faults as a source of line broadening. Variations in the lattice constant with the type of reflexion could not be detected. An appreciable line-broadening is seen to result from the explosive shock under the conditions of both hard and soft impact.

No traces of martensite have been detected.

6.4 Discussion

The principal objective for this investigation is to study whether explosive forming may have detrimental side effects on the properties of stainless steels and how these effects can be avoided. It is indicated that structural effects, as revealed by the metallographical examination, arise mainly through the impact with the die. Under conditions of hard impact a number of deformation twins can be formed, even if the peak pressure of the incident shock wave is not sufficient to initiate twinning.

The x-ray studies indicate, on the other hand, a marked increase in the lattice strain and fault density to result from explosive forming also under conditions of "soft impact", although not to the same extent as by "hard impact".

6.5 Further Work

The investigation will be continued on other types of steel, as mentioned in a previous report, and corrosion- and mechanical testing will be carried out. The conditions leading to the "impact effect" will be studied in more detail.

7.0 HIGH TEMPERATURE FORMING DIE

7.1 Introduction

The general principles of a high temperature forming die and a discussion of its intended field of application were given in status report No. 1. It was emphasized that the main objective of the investigation is to study the combined effect of high temperatures, shock waves, and strain rates on plasticity, transformation characteristics and microstructure. Since the die construction is expected to permit quenching of the work piece immediately after forming, a number of interesting effects were predicted. A study of the technological aspects of the process is also part of the program. Ferritic, martensitic and austenitic steels, as well as tungsten and a titanium alloy will be investigated.

Construction and building of the die have been completed in the preceding phase of the work, but no actual experiments have as yet been carried out.

7.2 Design and Operation of the Die

Fig. 26 shows the construction principles of the high temperature forming die, and Fig. 27 presents a photograph of the die. The blank holder assembly consists of two steel rings of the following composition: 0.2 C - 20 Cr - 9 Ni - 2.5 W. The yield strength of this steel is 25 kg/mm^2 at 800 $^{\circ}C$, and the total weight of the assembly (without blank) is about 9 kg. The rings are thermally insulated from the die by a laminate of 0.2 mm nickel sheets and SiO_2 fabric. The optimum number of layers in the laminate will have to be determined experimentally. Three guiding knives (not shown in drawing) are situated along the inside periphery of the adapter ring, in order to obtain a quick alignment of the blank holder assembly in the die.

The cover plate holding ring rests on three uniformly spaced rollers fixed to the cover flange. The rollers fit into a helical

groove (inclined 35^{o}) in the outer surface of the cover plate, holding ring. The ring is arrested by a horizontal pin, operated by a pneumatic release mechanism. When the pin is withdrawn, the cover plate holding ring rotates into a position close to the blank. This motion triggers the shot.

Vacuum sealing between die and cover plate is provided by a thin rubber sheet stretched over the entire upper surface of the assembled die. An auxiliary O-ring groove is machined in the surface, in order to obtain positive sealing by means of a clamping device. Evacuation of the die occurs simultaneously on both sides of the blank, due to the porous nature of the thermal insulation at the draw ring.

The blank assembly together with insulation is heated separately in a furnace with atmospheric control. When the desired temperature is reached, the assembly is quickly transfered to the die where the cover flange is immediately closed, and the system is evacuated. After the charge has been mounted, the die is transfered to the water pit and fired. The time lapse between transfer of blank from the furnace and firing of the shot is estimated to 2 á 3 minutes.

For calculation of the heat losses in a 2 mm thick stainless steel blank originally at 800 ^{o}C, two assumptions have been made.

1. The temperature of the blank holder assembly remains constant throughout the experiment.
2. An average coefficient of emissivity of 0.05 applies to the blank surroundings.

   The following temperature differences between center and draw ring area will then occur:

   100 ^{o}C after 2 minutes
   140 ^{o}C " 3 "
   180 ^{o}C " 5 "

Placing the steel blank between two thin copper sheets will reduce these temperature differences very appreciably since heat transport from the holding rings is increased several times. Special insulating methods can also be resorted to, if required.

7.3 Further Work

The work in the following six months will comprise the following items:

1. Trimming of all operating mechanisms and instruments for optimum reliability.
2. Study of cooling conditions before and after forming and energy transfer to the blank through cover plate and possibly insulation.
3. Initial experiments with the steels, selected for the main investigation.
4. Adaption of the die for forming of 6" diameter tungsten blanks.

8.0 EXPLOSIVE WELDING

8.1 Introduction

The general purpose of this program is to study the effect of welding conditions on the physical and chemical interactions occuring in the weld zone and further to correlate these with the mechanical properties of the weld. The ultimate goal is to define optimum parameters for industrial cladding processes involving refractory metals and stainless steels combined with structural metals such as mild steel and aluminum.

The importance of surface cleaning, relative position of the plates, air pressure (vacuum or full atmosphere), type and amount of explosive and modification of the shock profile by interlayers between the explosive and the plate, have been studied in recent investigations. The results, however, are inconsistent, indicating that slight variations of the process parameters may have a marked effect upon the weld properties. Further studies are thus clearly needed for improvement of weld quality and process control.

The initial studies under this contract have mainly been concerned with the three combinations of stainless steel (18/8 + 1.5 Mo) and aluminum (99.5 Al). The technologically most interesting of these combinations is stainless steel to aluminum, but Davenport (9) have claimed that the weldability is very poor in this case. The preliminary results given below seem to confirm this, but ways of getting around the difficulties are indicated.

8.2 Experimental Conditions

The following parameters have been varied as indicated in Table II:

1. Material combination.
2. Relative position of the plates.

3. Surface cleaning.
4. Shock wave characteristics.
5. Plate thickness.

Fig. 28 shows a schematic drawing of the experimental arrangement. The plates were 6 x 8 cm^2 and the explosive 6 x 9 cm^2. Detonation was initiated at a point outside of the plate surface.

The metal surfaces were either 1) pickled or 2) pickled and ground on fine emery paper (1F). Pickling of aluminum was done in a 20 % sodium hydroxide solution and stainless steel in a solution containing 20 vol. % of conc. hydrocloric acid, 10 vol. % conc. nitric acid and water.

METABEL sheet explosive from ICI has been used in all experiments. The following specifications are quoted by the producer:

Thickness:	1/8 inch.
Detonation velocity:	6500-7500 m/sec. Probably in the upper region.
Density:	So = 1.47 g/cm^3
Chapman - Jouguet density:	C - J = 1.96 g/cm^3
Detonation pressures:	At 7500 m/sec - 215 KB At 6500 m/sec - 155 KB

8.3 Results and Discussion

The welded specimens were sectioned along the centerline parallel to the direction of shock wave propagation. The welded fraction of the centerline is recorded in Table II.

Figures 29 to 33 show photomicrographs of weld zones, Fig. 29 demonstrating the thick alloy layer resulting when the plates are placed at an angle and Fig. 30 the much thinner layer resulting when the plates are in contact. Typical rippel formation was never observed in welds between stainless steel and aluminum.

Fig. 31 shows a weld which has failed after the formation of an intermetallic layer. It is seen that fracturing invariably occurs in the intermetallic layer itself or in its boundaries.

Fig. 32 shows an aluminum to aluminum weld in which characteristic ripple formation is observed. A columnar structure in some localized areas between the ripples, indicates that regular melting must have occured. In other areas, indications of recrystallization and grain growth are prominent. Fig. 33 shows the unusually heavy ripple formation which is caused by large angles between the plates. Again, indications of melting can easily be identified.

Importance of the relative position of the plates is demonstrated in Table II where the length of the welded fraction of the centerline is given. For stainless steel to aluminum welds, the angle apparently has to be less than about 4° in order to suppress failure by fracturing in the intermetallic layer. The best results were obtained when angles of 1° were used. However, comparable weld lengths results when the plates were parallel at a spacing of 1 mm. When the plates were in direct contact over the entire surface, very little welding took place.

The effect of sheet rubber interlayers, for the modification of the shock wave, is not very distinct in these experiments. The fact that welding is prevented when a rubber sheet of 12 mm is used, is of little practical importance. However, shock wave modification may become necessary for protection of the metal against undesirable structural changes.

Microhardness measurements taken across an aluminum to aluminum weld showed that the hardness varied slightly from grain to grain, but the weld zone was usually not much different from the bulk of the material with a hardness of 42 kg/mm^2. The same hardness was also found in an unwelded reference plate. Within the localized areas with columnar structure, a hardness of about 70 kg/mm^2 was found.

In stainless steel to aluminum welds, a hardness of about 47 kg/mm^2 was measured near the intermetallic zone on the aluminum

side. Within the intermetallic zone itself the hardness was about 480 kg/mm^2.

The above results indicate that in order for welding of stainless steel to aluminum to become possible, very thin intermetallic layers should be formed.

8.4 Further Work

The studies of the influence of process variables on the weld zone will be continued, this time also introducing vacuum between the plates as a new parameter.

Further studies of the effect of shock wave modification will be carried out, special attention being paid to mechanical properties and stress corrosion resistance.

In addition to the material combinations already studied, titanium/ stainless steel and tantalum/stainless steel will also be incorporated in the investigation.

Table II.

Explosive welding experiments.

Exp. No.	Testmaterials upper plate	lower plate	Plate thickness, mm upper plate	lower plate	Plate arr.	Surf. treatm.	Rubber inter layer, mm plate/ anvil	plate/ explos.	% of center line welded	Aver. thickn. alloy interl., μ
1	18/8 +1,5 Mo	Al 2S	1	3	2° angle	pickled	0	6	16	10
2	"	"	"	"	4° "	"	"	"	10	15
3	"	"	"	"	8° "	"	"	"	0	
4	"	"	"	"	1° "	"	"	"	60	10
5	"	"	"	"	contact	"	"	"	10	3
6	"	"	"	"	1° angle	"	"	12	2	
7	"	"	"	"	"	"	6	6	10	10
8	Al 2S	18/8 +1,5 Mo	3	1	"	"	0	"	10	12
9	"	"	"	"	"	"	6	"	60	10
10	18/8 +1,5 Mo	Al 2S	1	3	"	pickled +emery	1	4	25	10
11	"	"	"	"	"	"	"	8	10	5
12	"	"	"	"	contact	"	"	4	12	4
13	"	"	"	"	"	"	"	8	10	6
14	"	"	"	"	1° angle	"	"	"	10	
15	"	"	"	"	"	"	"	"	35	15
16	"	"	"	"	"	"	"	"	10	10
17	"	"	"	"	"	"	"	"	2	10
16a	18/8 +1,5Mo	Al 2S	0,5	3	1 mm spacing	pickled	0	6	50	8
17a	"	"	"	"	"	"	"	"	80	15

Table II - cont.

Exp. No.	Testmaterials upper plate	lower plate	Plate thickness, mm upper plate	lower plate	Plate arr.	Surf. treatm.	Rubber inter-layer, mm plate/anvil	plate/explos.	% of center line welded	Aver. thickn. alloy interl.,
18	18/8 +1,5 Mo	Al 2S	0,5	3	2 mm spacing	pickled	0	6	2	
19	"	"	"	"	"	"	"	"	20	
20	Al 2S	Al 2S	3	"	1 mm spacing	"	"	"	70	
21	"	"	"	3	"	"	"	"	60	
22	"	"	"	"	2 mm spacing	"	"	"	2-5	
23	"	"	"	"	"	"	"	"	lost	
24	18/8+ 1,5 Mo	18/8+ 1,5 Mo	0,5	0,5	1 mm spacing	"	"	"	10	
25	"	"	"	"	2 mm spacing	"	"	"	10	
26	"	"	"	"	"	"	"	"	10	
27	"	"	"	"	"	"	"	"	10	
28	Al 2S	Al 2S	3	3	contact	"	"	"	20	
29	"	"	"	"	"	"	"	"	40	
30	18/8+ 1,5 Mo	18/8+ 1,5 Mo	0,5	0,5	"	"	"	"	lost	
31	"	"	"	"	"	"	"	"	10	
32	18/8+ 1,5 Mo	Al 2S	0,5	3	1^{o}angle	"	"	"	20	5
33	"	"	"	"	"	"	"	"	lost	
34	"	"	"	"	1 mm spacing	"	"	"	30	10
35	"	"	"	"	"	"	"	"	50	15
36	"	"	"	"	contact	"	"	"	5	5
37	"	"	"	"	"	"	"	"	0	0

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LIST OF ILLUSTRATIONS.

Fig. 28. Experimental setup for explosive cladding with parallel plates.

Fig. 29. Stainless steel - aluminium weld. Heavy alloy formation. Unetched, x 400.

Fig. 30. Stainless steel - aluminium weld. Slight alloy formation. Unetched, x 400.

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Fig. 32. Aluminium - aluminium weld with ripple formation. Indication of melted areas and recrystallization between ripples. Prepared by microtome, electrolytically polished and etched in NaOH sol., x 150.

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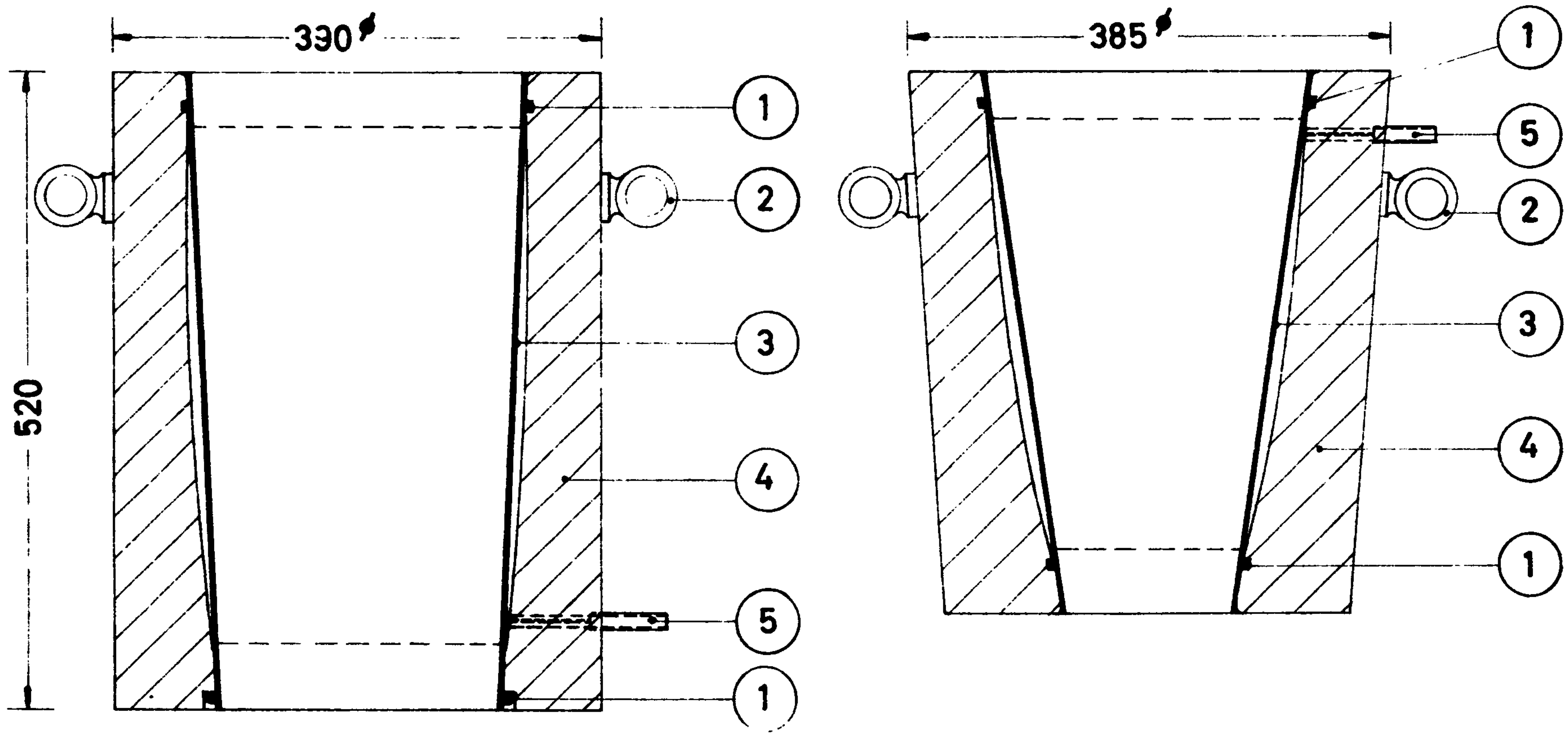
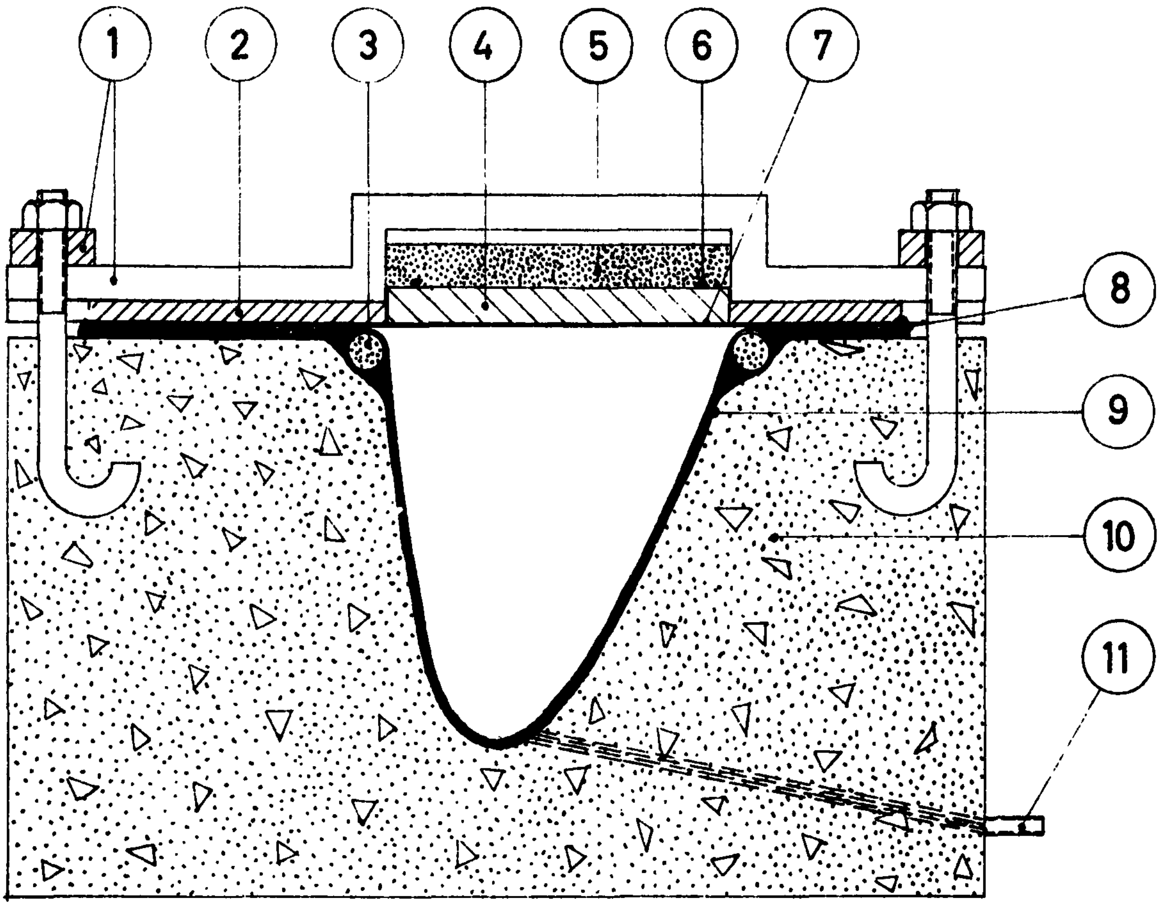


1. C-ring seals
2. Eye bolt
3. Work piece
4. Die
5. Vacuum line

Fig. 1. Dies for sizing of rocket nose cone sections.

Fig. 2. Rocket nose cone sections, explosively sized under water.

Fig. 3. Die assembly for forming of air intake ducts. Result of preliminary experiments in background.



1. Clamps
2. Cover flange
3. Draw ring
4. Rubber pad
5. Sand layer
6. Detonating fuse
7. Work piece
8. Plasticine sealing
9. Epoxy lining
10. Reinforced concrete
11. Vacuum line

Fig. 4. Forming die for air intake ducts.

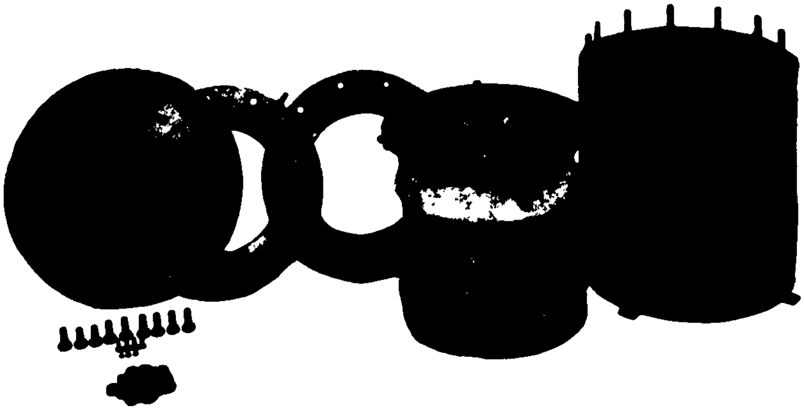
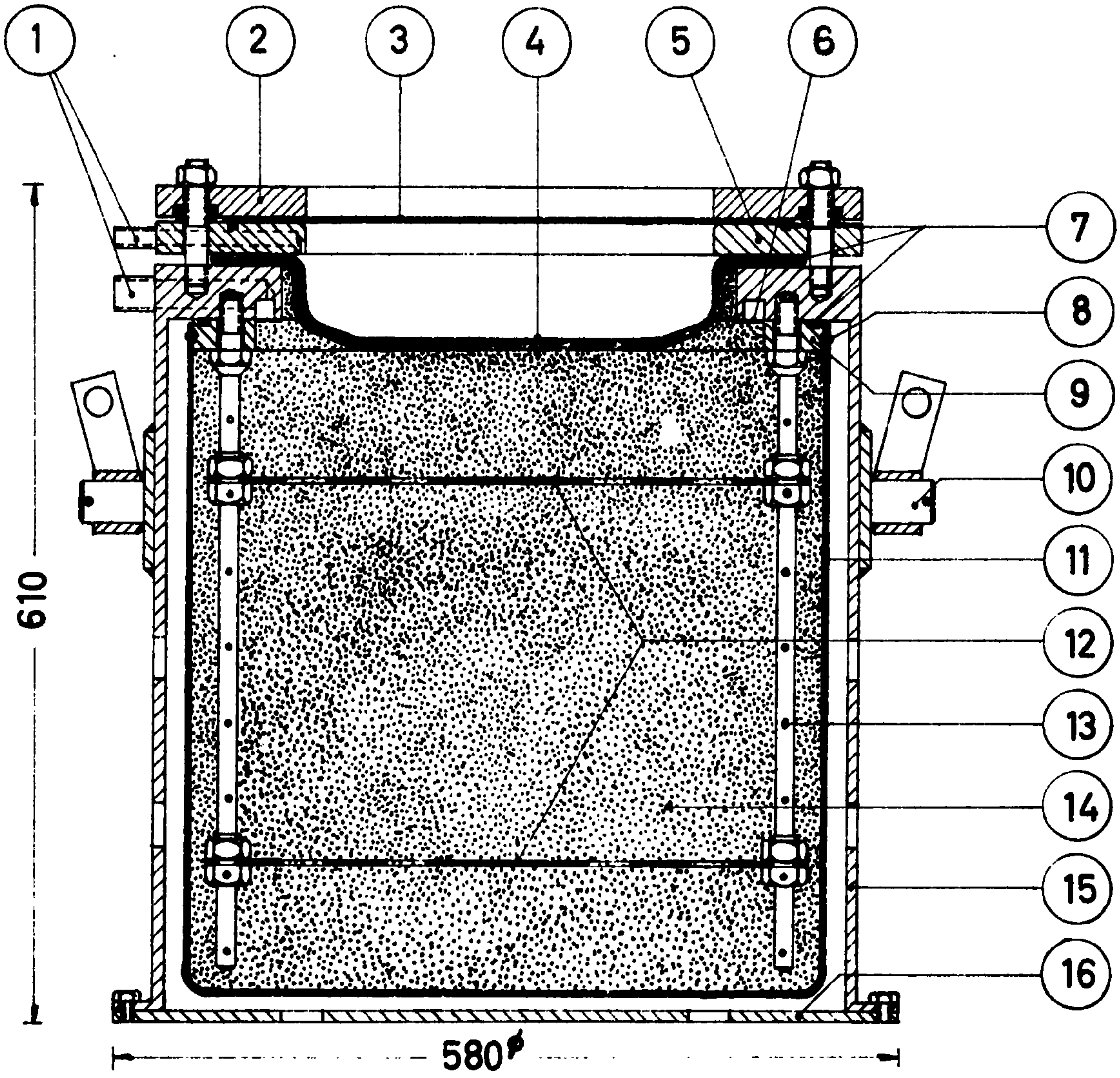
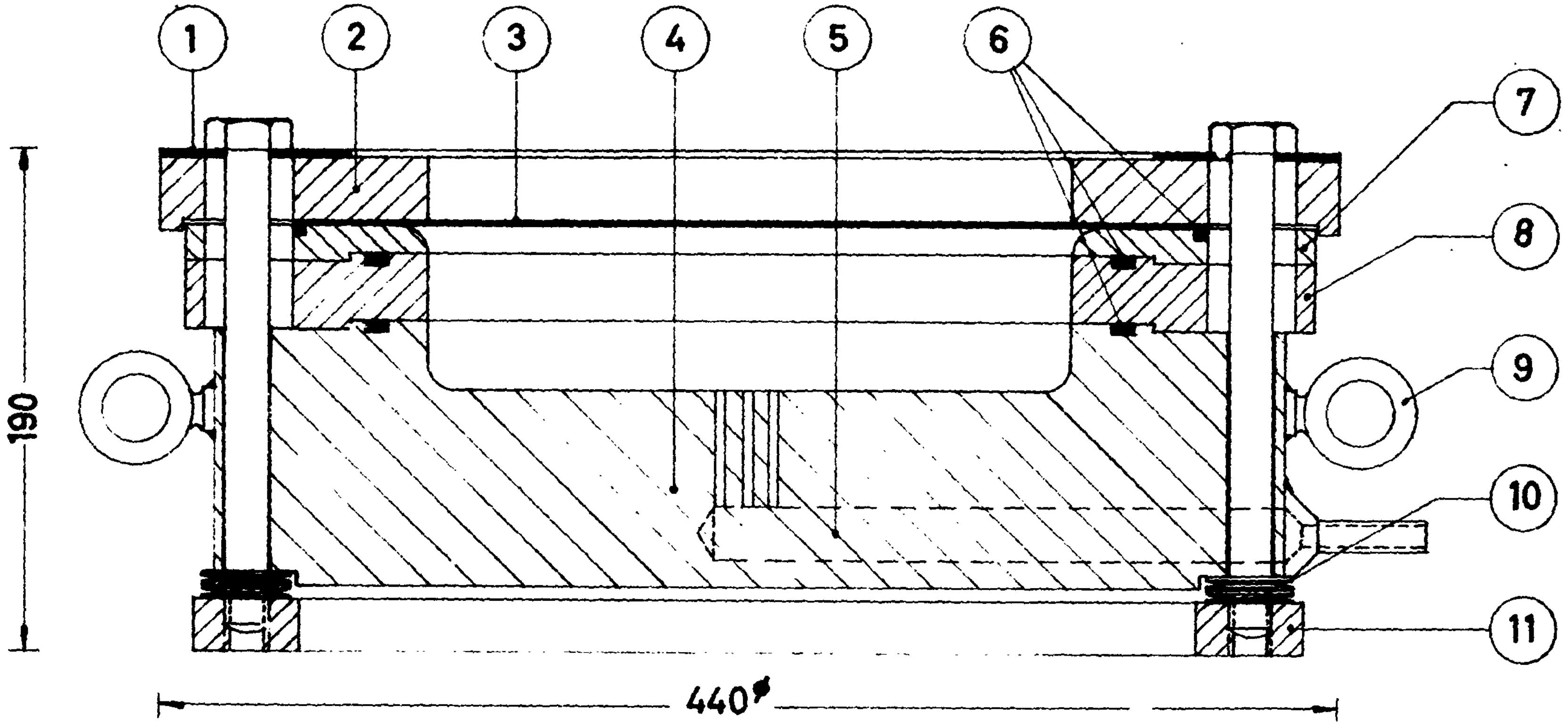


Fig. 5. Vacuum compacted sand die.



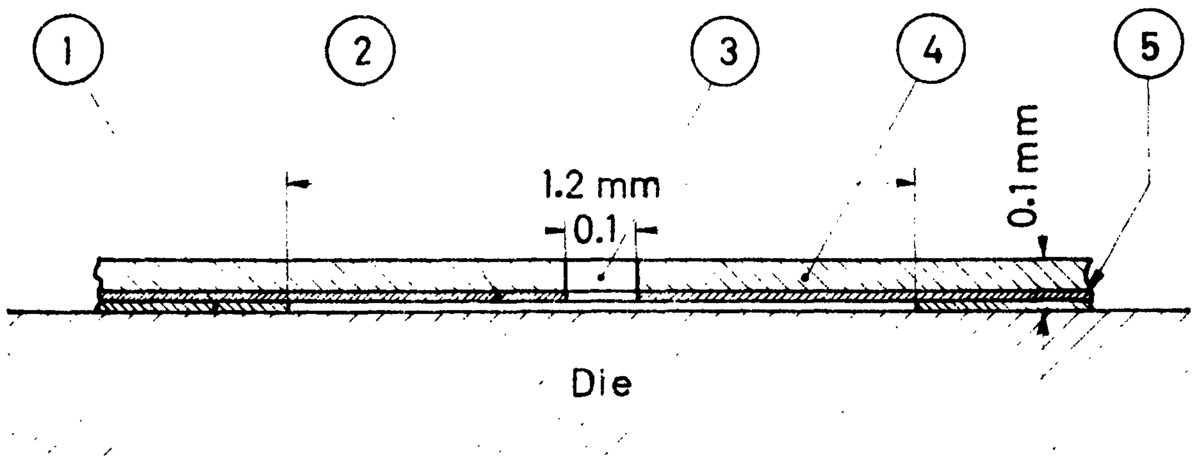
1. Vacuum lines
2. Cover flange
3. Work piece
4. Epoxy shell
5. Draw ring
6. Rock wool filter
7. O-ring seals
8. Clamping ring
9. Rubber bag support
10. Revolving hinge
11. Rubber bag
12. Perforated reinforcement plate
13. Plate fastening rod
14. Dry sand
15. Housing
16. Bottom plate

Fig. 6. Vacuum compacted sand die with exchangeable epoxy shell



1. Lock ring
2. Cover flange
3. Work piece
4. Die
5. Vacuum line
6. O-ring seals
7. Draw ring
8. Adapter ring
9. Eye bolt
10. Disk springs
11. Threaded bottom die

Fig. 7. Cold forming die of mild steel.



1. Insulating tape
2. Aluminium ribbon
3. Air vent
4. Insulating tape
5. Adhesive surface

Fig. 8. Planar contact.

Fig. 9. Signals from planar contact on top of blank and pin contact 0.4 mm below blank.

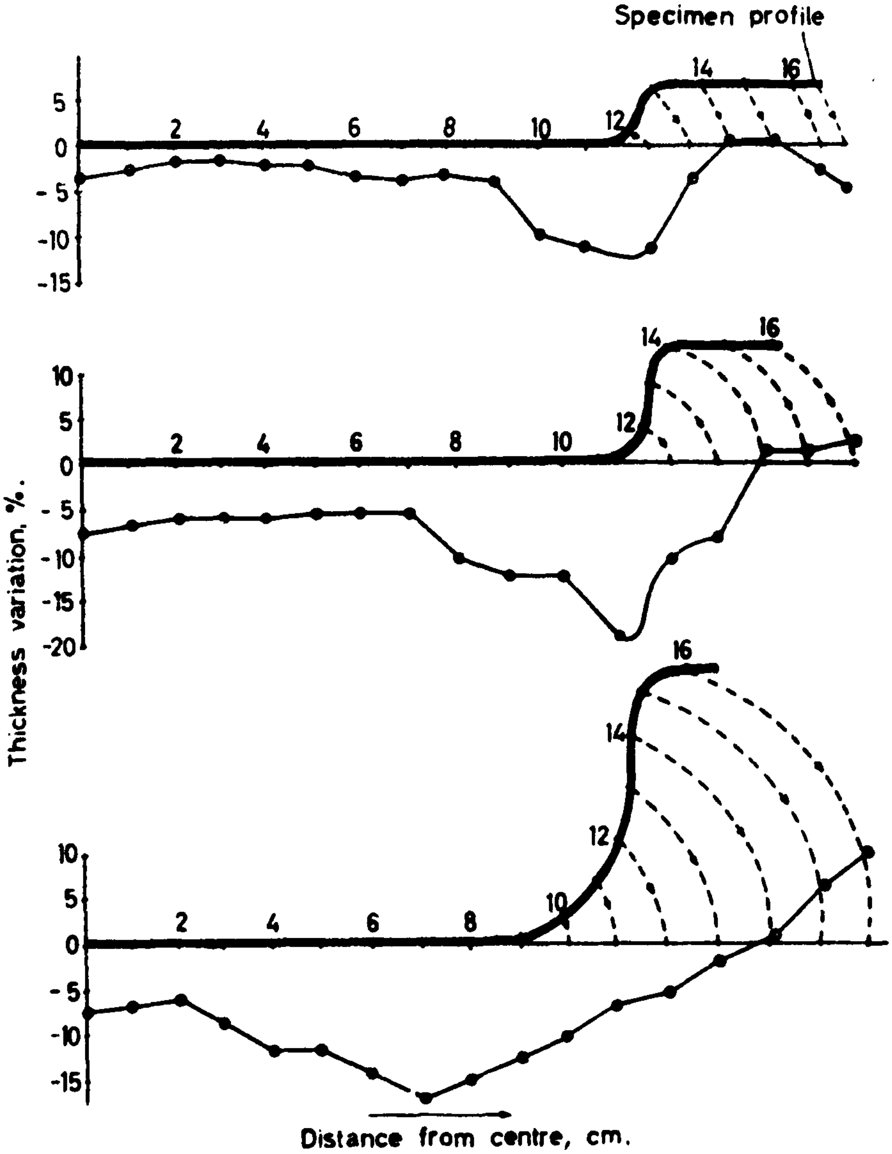


Fig. 10. Thinning as a function of distance from centre of blank at three deformation stages.

Fig. 11.

Fig. 12.

Fig. 13.

Fig. 14.

	Type of steel	Orientation relative to shock	Retardation balsa wood	Impact with die	Depth of draw mm	Magnification
Fig. 11	SAE 304	—	as annealed		—	X 100
Fig. 12	SAE 304	parallel to	—	yes	13	X 100
Fig. 13	SAE 304	parallel to	yes	—	20	X 100
Fig. 14	SAE 304	parallel to	—	yes	25	X 100

Fig. 15.

Fig. 16.

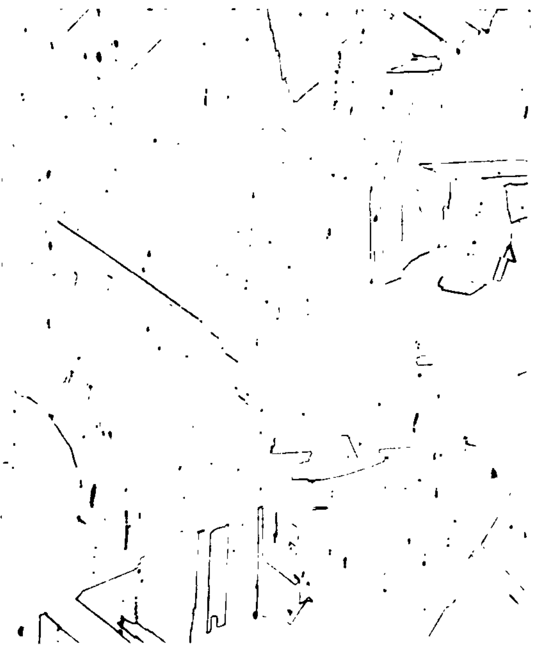


Fig. 17.

Fig. 18.

	Type of steel	Orientation relative to shock	Retardation balsa wood	Impact with die	Depth of draw mm	Magnification
Fig. 15	SAE 304	parallel to	—	yes	60	X 100
Fig. 16	SAE 304	normal to	—	yes	13	X 100
Fig. 17	SAE 304	normal to	yes	—	20	X 100
Fig. 18	SAE 304	normal to	—	yes	25	X 100

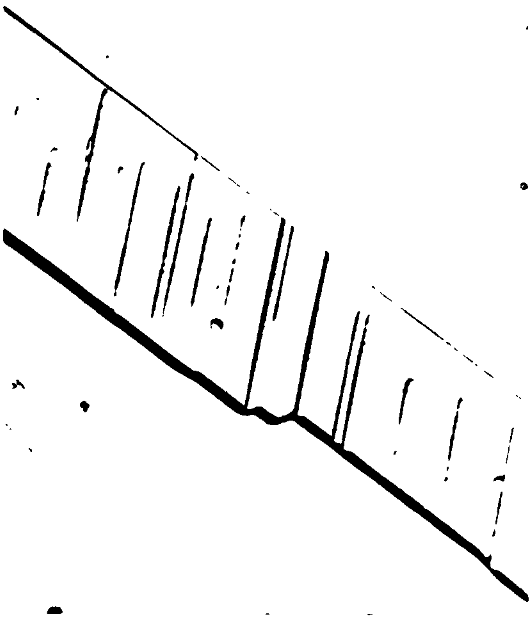


Fig. 19

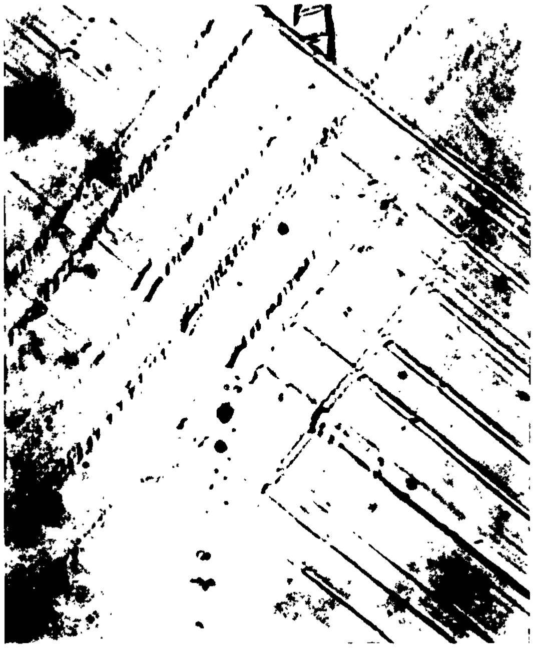


Fig. 20.

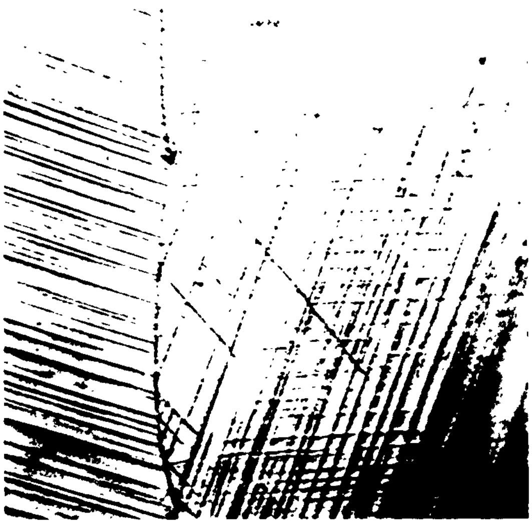


Fig. 21.

Fig. 22.

	Type of steel	Orientation relative to shock	Retardation balsa wood	Impact with die	Depth of draw mm	Magnification
Fig. 19	SAE 304	normal to	—	yes	13	X 1250
Fig. 20	SAE 304	normal to	—	yes	13	X 1250
Fig. 21	SAE 304	normal to	—	yes	25	X 1250
Fig. 22	SAE 304	normal to	—	yes	25	X 400

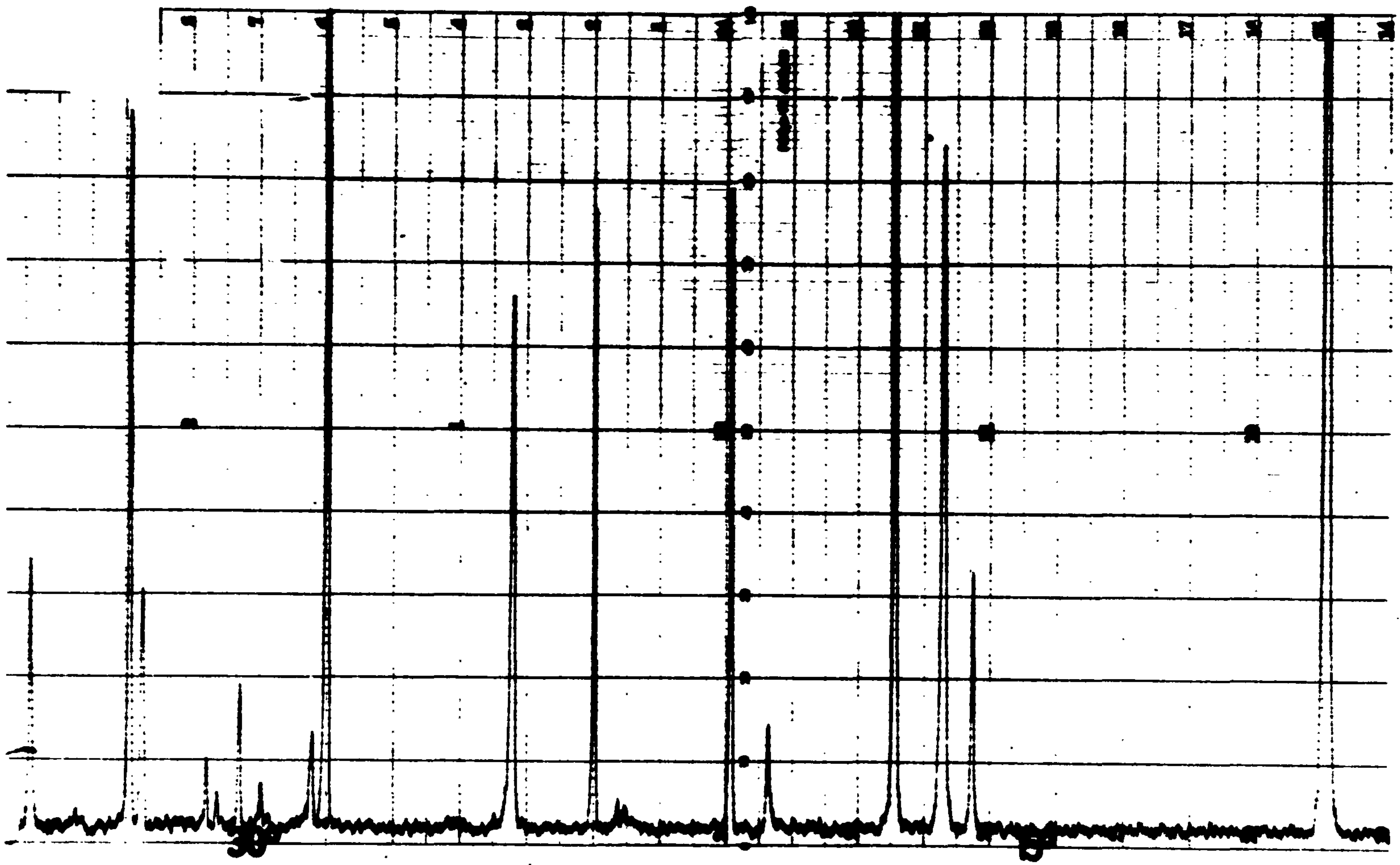


Fig. 23. Part of texture diffractogram of SAE 304 steel as annealed. Stationary specimen, irradiated area about 5 mm^2, (200) reflections, Co radiation.

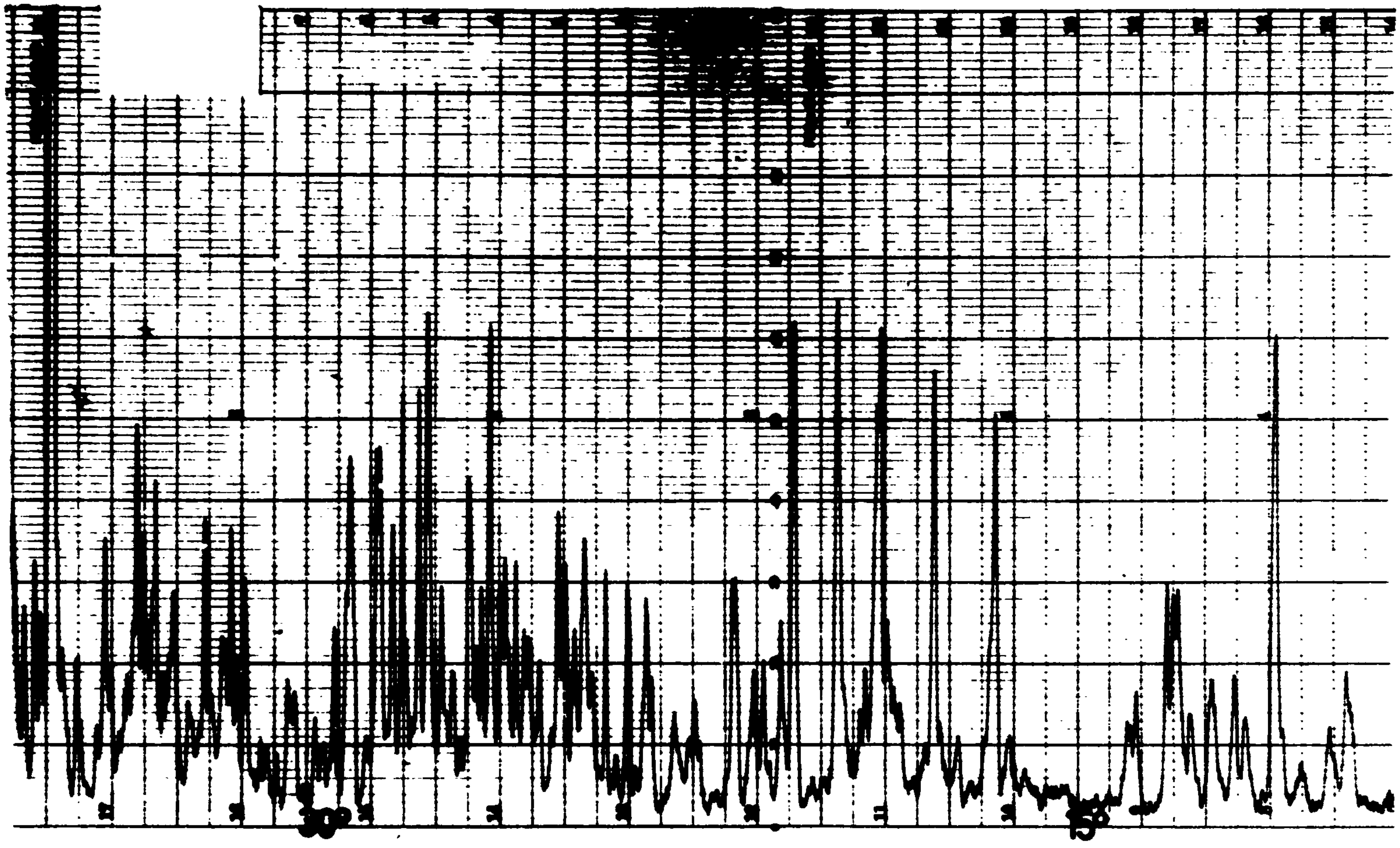


Fig. 24. Part of texture diffractogram of SAE 304 steel after retardation by balsa wood (as in Fig. 13 and 17). Stationary specimen, irradiated area about 5 mm^2, (200) reflections and Co radiation.

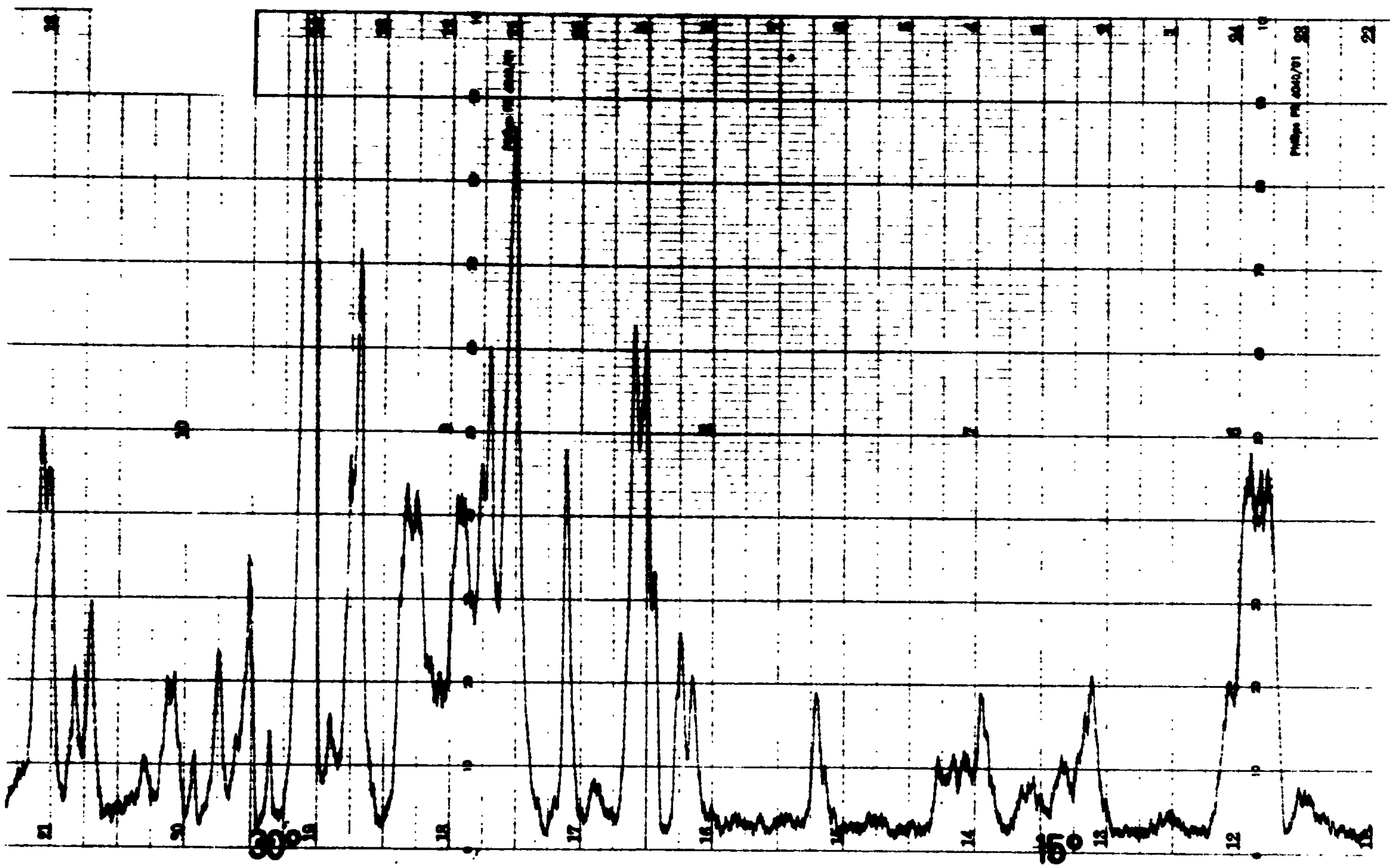
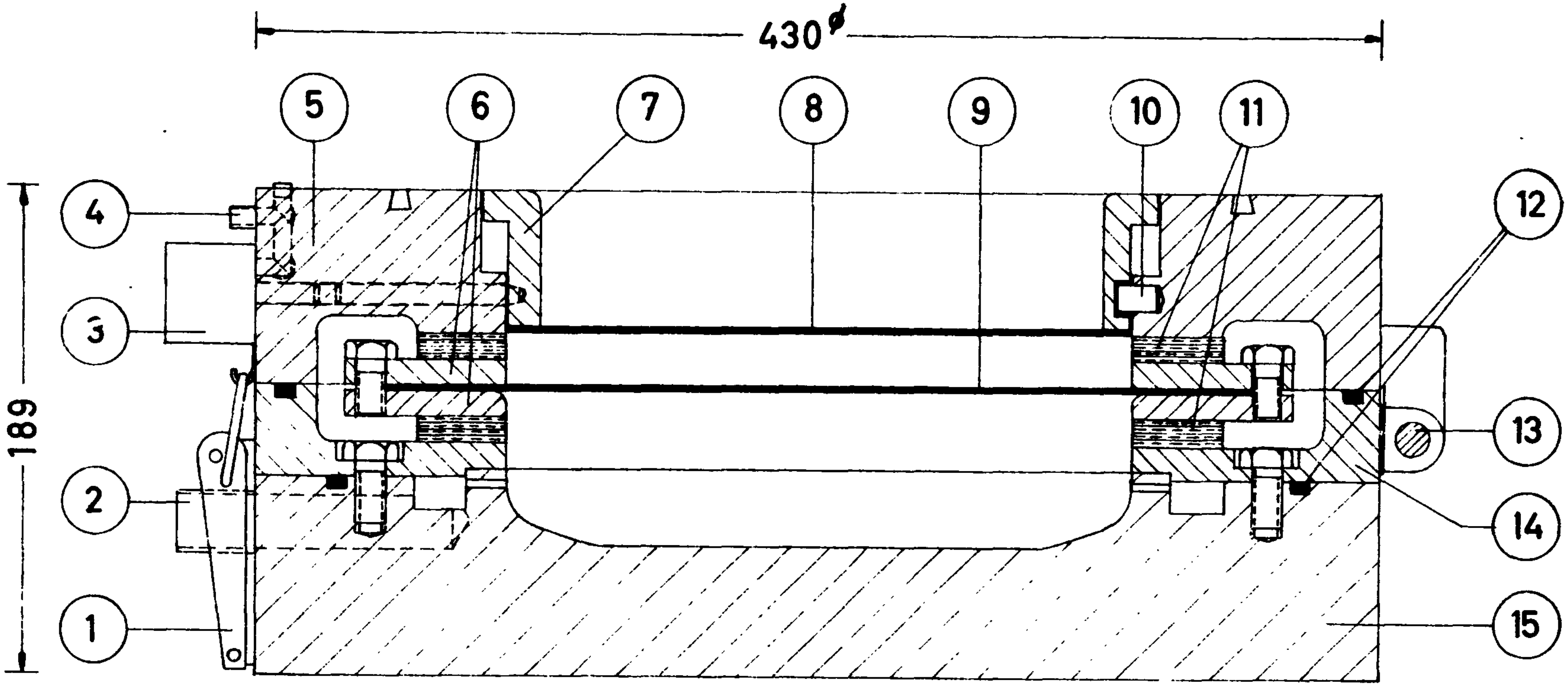


Fig. 25. Part of texture diffractogram of SAE 304 steel after drawing and impact with die (as in Fig. 14 and 18). Stationary specimen, irradiated area about 5 mm^2, (200) reflections and Co radiation.



1. Fastening mechanism
2. Vacuum line
3. Cover plate release mechanism
4. Compressed air inlet
5. Cover flange
6. Blank holder assembly
7. Cover plate holding ring
8. Cover plate
9. Work piece
10. Roller
11. Thermal insulation
12. O-ring seals
13. Hinge
14. Adapter ring
15. Die

Fig. 26. High temperature forming die.

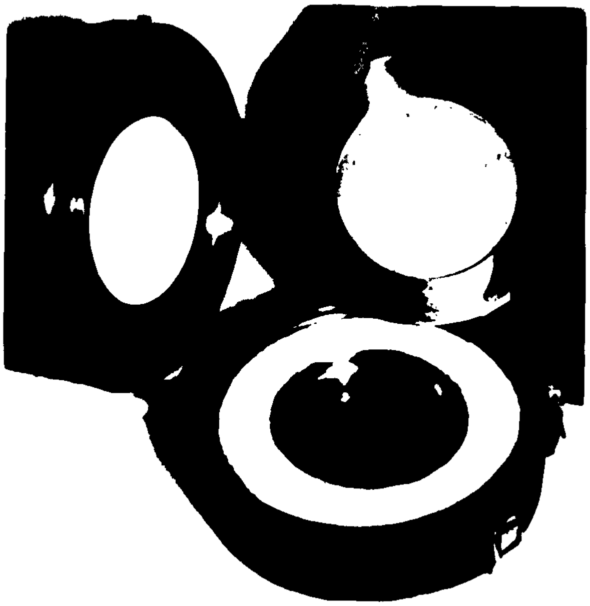
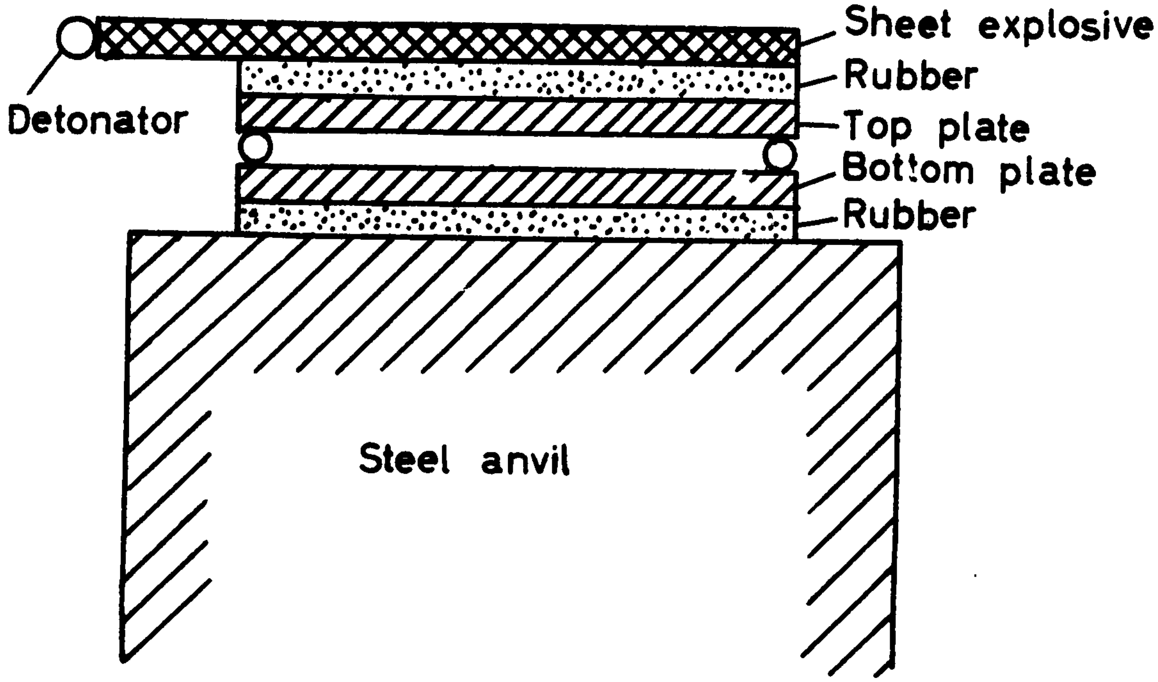


Fig. 27. High temperature forming die.



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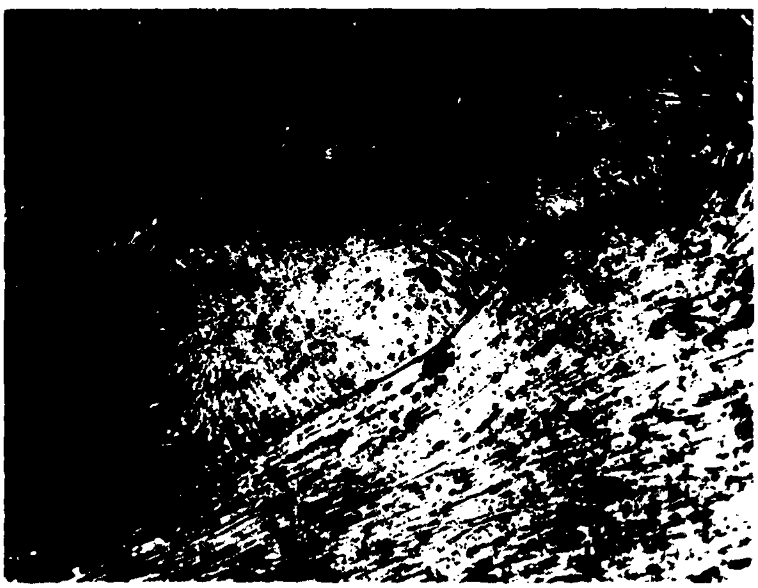

Fig. 33. Aluminium — aluminium weld with heavy ripple formation. Columnar structure in melted areas. Prepared by microtome, electrolytihally polished and etched in NaOH sol., x 400.

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